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Flexural buckling resistance of welded HSS box section members

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ABSTRACT

The exact consideration of the global buckling behaviour of HSS steel structures is very important in the design because due to the higher yield strength smaller cross sections can be used, which might be more sensitive to stability failure. According to the previous research results, the flexural buckling behaviour of HSS and NSS columns can be significantly different, however, these differences are not considered in the current design methods. The application range of the current EN 1993-1-1 [1] is limited for steel grades up to S460. The EN 1993-1-12 [2] gives design rules for materials up to steel grades of S700, however, for the determination of the flexural buckling resistance of welded box section members there are no improved design guidelines for HSS structures. Therefore, the purpose of the current study is to investigate the column buckling behaviour of HSS welded box section columns based on previous and current experimental investigations and on numerical simulations. This paper focuses on the effect of the different material properties, imperfections and residual stresses on the global buckling behaviour of HSS members and gives design proposal for the applicable column buckling curves for steel grades between S420 and S960.

1. Introduction

The application field of high strength steel (HSS – S420 and higher steel grades up to S960) is growing nowadays in the civil engineering praxis due to the numerous advantages of the HSS members compared to the normal strength steel (NSS – S235, S275, S355) structures: economic design, material saving, possibility of creation of lighter and more aesthetic structures. The application range of the current EN 1993-1-1 [1] is limited to ordinary steel materials up to the steel grade of S460. EN 1993-1-12 [2] gives design background for materials up to steel grades of S700, however, for the determination of the column buckling resistance of welded box sections the same rules are given for materials between steel grades of S460–S700 as for S460. However, several previous research results [3,10,15] prove that the flexural buckling behaviour of HSS structures is more favourable than that of NSS structures. The differences in the flexural buckling behaviour come from the (i) different residual stresses, (ii) different material properties and (iii) geometric imperfections. Numerous previous investigations and residual stress measurements prove that the residual stress amplitudes are smaller for HSS structures compared to the yield strength than for NSS members [11,13]. This results in significant benefits in the flexural buckling resistance, and it can be expected that higher column buckling curves can be used for HSS members than for NSS members. The general aim of the current research is to investigate the flexural buckling behaviour of HSS welded box section columns within the steel grade range of S235–S960. Based on the experimental and numerical investigation our aim is to propose safe and economic design buckling curve for HSS welded box section columns.

There are only a limited number of column buckling tests available in the international literature dealing with HSS welded box section columns. The objective of our current research is to collect the available results from the international literature and to perform a new experimental and numerical research program to investigate the flexural buckling behaviour of HSS structures. A total of 49 large-scale tests are carried out in the Structural Laboratory of the Budapest University of Technology and Economics Department of Structural Engineering in 2015. Test specimens are manufactured having steel grades of S235–S960. The aim of the tests with the wide analysed steel grade range is to give reference and comparison background to the test results made on HSS members (S500–S960) and to cover a wide range of steel grades used in the civil engineering praxis. All the previous test programs investigated the flexural buckling behaviour of one specific steel grade. Our aim is to determine the flexural buckling resistance of columns having different steel grades using the same manufacturing process, test equipment and evaluation process.

Parallel to the experimental research program a detailed numerical investigation is also carried out to determine the flexural buckling resistance of HSS box section columns and to investigate the differences between NSS and HSS members. The numerical research program concluded that the differences in the flexural buckling behaviour come

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from (i) the different yield strength, (ii) the different residual stress pattern and (iii) the different material properties. Based on the current and the previous experimental results and based on the current numerical investigations the differences in the flexural buckling behaviour of HSS and NSS members are identified, studied and evaluated. Finally applicable design buckling curves are proposed for welded HSS box section members. The objectives of the research program are achieved by the following research strategy:

1. literature review on buckling tests of HSS welded box section members,
2. flexural buckling tests on welded NSS and HSS members with different global slenderness and steel grades (S235, S355, S420, S460, S500, S700 and S960),
3. evaluation and documentation of the test results,
4. numerical parametric study to investigate the flexural buckling behaviour of HSS structures compared to NSS members,
5. investigation of the differences in the structural behaviour coming from the different (i) material properties, (ii) geometric imperfections and (iii) residual stress patterns and magnitudes,
6. proposal for applicable column buckling curve based on present and previous test results and based on the numerical parametric study.

2. Literature overview

2.1. General observations

There are a relative large number of previous investigations available in the international literature dealing with the global (flexural) buckling behaviour of NSS box section members. But there are only a limited number of previous investigations dealing with HSS square box sections. The following publications listed below are found by the authors dealing with HSS box or hollow section columns:

- 1970 – Nishino and Tall [3];
- 1983 – Fukumoto and Itoh [4];
- 1994 – Rasmussen and Hancock [5];
- 2012 – Pavlovčič, Froschmeier, Kuhlmann and Beg [6];
- 2012 – Ban, Shi, Shi and Wang [7];
- 2013 – Ban, Shi, Shi and Bradford [8];
- 2014 – Wang, Li, Chen and Sun [9];
- 2014 – Design guidelines of the SSAB [10].

It can be observed from the list, that there are several early publications from 1970 to 1994 investigating the flexural buckling resistance of HSS columns. All the results showed that based on the yield strength the normalized flexural buckling resistance is larger for HSS members compared to specimens manufactured from NSS. The experiments also showed that the nature of the buckling phenomenon of the HSS columns are different from the NSS structures, which comes from the different residual stress pattern, geometric imperfections (manufacturing quality) and different material properties. Between 2012 and 2014 an intensive research activity was started in this subject especially in China, Australia and also in Europe in frame of the RUOSTE: Rules On High-Strength Steel RFCS Project (RFSR-CT-2012-00036). The main aim of these investigations are not only the characterisation of the flexural buckling resistance for HSS box sections, but also the standardization and the selection of applicable column buckling curves. The specialties of our current investigation is that all the previous research activities were focusing on a specific new steel grade (S420, S460, S690 or S960) and the flexural buckling behaviour was characterised for that specific steel material. Our current investigation focuses on a wide range of steel grades (S235, S355, S420, S460, S500; S700 and S960) ensuring the comparison possibility using the same loading equipment, support conditions and the same evaluation process.

2.2. Results of the previous investigations on HSS structures

Nishino and Tall performed tests on columns having rolled or welded box section and H-type cross sections made from high strength steel ASTM514 with a nominal yield strength of 690 MPa [3]. Four tests were executed on welded box sections with pinned support conditions loaded by compression force. The tested columns were positioned in the test such a way that the effect of the end-eccentricity and the initial out-of-straightness counteract approximately each other. Therefore the columns failed on a very high load level nearly by the perfect bifurcation point. The test setup, and the elimination of the geometric imperfections was in accordance with the American design philosophy which was based on the resistance of the straight and centrically loaded column and the effect of the imperfections were covered by a relatively large safety factor. Consequently, these tests cannot be used in the current evaluation process and to select a flexural buckling curve of HSS box section members, thus the EN1993-1-1 [1] is based on the resistances of columns having overall geometric imperfections of L/1000 and residual stresses coming from the manufacturing process.

Fukumoto and Itoh collected a total of 1665 individual column test results stored in an experimental database [4]. The database contained cross sections of rolled and welded H-profiles, welded box section, square and circular tubes, circular solid sections and T-profiles. This huge number of test results are statistically evaluated and compared to the EN 1993-1-1 column buckling curves separately for all the cross section types. Among the test specimens there were 316 box and square tubes manufactured from annealed NSS and HSS materials. The statistical evaluation is conducted for the whole population of the test results without considering the steel grade. Authors observed significant difference between the nominal and the actual yield strength of the investigated materials, therefore the statistical evaluation is executed based on the actual as well as on the nominal yield strength. The authors compared the test results to the column buckling **curve b**. The mean value of all the tests considering the actual yield strength is equal to 1.4 with a 2.3% lower quantile value of 0.877. Considering the nominal yield strength the mean value is equal to 1.147 with a 2.3% lower quantile of 0.817. In the same time the test results showed that nine of the annealed welded box columns with HSS material would be allocated to the buckling **curve a_0**. Based on the statistical evaluation the authors concluded that the annealed box section columns possess strengths about 20–30% higher than the NSS columns and even 10% higher than HSS columns. But HSS columns showed definitely larger resistances (normalized by the yield strength) than NSS columns.

Rasmussen and Hancock performed flexural buckling tests on 13 welded box and I-section specimens investigating the local and global buckling behaviour [5]. The specimens are manufactured from BISALLOY80 steel plates with nominal yield strength of 690 MPa. The aim of the tests was to characterise the buckling behaviour of high strength steel columns and to determine the appropriate slenderness dependent reduction factor and to propose applicable buckling curve from the multiple buckling curves used in different standards. From the 6 specimens two short (700 mm), two medium (1950 mm) and two long (3451 mm) specimens are investigated analysing dominantly different global slenderness ranges. From each specimen group one specimen was loaded centrically, and the other eccentrically. The residual stress pattern of the test specimens were also measured and evaluated. The evaluation of the test results showed that the eccentrically loaded specimen resulted 6% lower resistance, than the centrically loaded columns. The authors concluded that the European buckling **curve b** is conservative for the investigated columns especially at the intermediate and large slenderness region. The design buckling curve of the American and Australian standards give closer approximation of the test results that is closer to the European buckling **curve a**. Therefore, it is proposed to use **curve a** for the box section columns manufactured from S690 steel material.

Four buckling tests were executed on centrically loaded rectangular-